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Intersubband population inversion under resonance tunneling in wide quantum well structures

Yu. A. Mityagin, V. N. Murzin, I. P. Kazakov, V. A. Chuenkov, A. L. Karuzskii, A. V. Perestoronin, A. A. Pishchulin and L. Yu. Shchurova
P. N. Lebedev Physical Institute, Leninsky pr. 53, 117924 Moscow, Russia

Abstract. Theoretical estimates and the results of vertical transport and optical investigations in GaAs/AlGaAs structures show that resonant tunneling can lead efficiently to selective depopulation of the levels, resulting in a population inversion and possible stimulated emission due to intersubband transitions between the lowest states in wide-quantum-well structures.

The recent investigations of intersubband infrared quantum cascade and quantum fountain lasers make a considerable step in nanostructure physics development but as to the far infrared range the problem has not been yet solved. In this paper we discuss a version of a far-infrared resonant tunneling laser based on the intersubband transitions in wide quantum well structures (WQWS) with the energy spacing between the two lowest states below the longitudinal-optic (LO) phonon energy. The population inversion is achieved due to the difference in scattering relaxation processes between the lowest states with or without LO phonon emission, and via the selective removal of carriers from the ground state by use of resonant tunneling to the neighboring quantum well [1, 2].

On the base of vertical transport and optical investigation of the structures the relaxation life-time and resonant tunneling rate values as well as the intersubband optical absorption and amplification and the other characteristics are discussed revealing the possibility of intersubband population inversion and far-infrared stimulated emission in the systems. The analysis of the intersubband relaxation in quantum wells is based on the theoretical approach resulting in the analytical expressions for optical phonons, acoustic phonons and electrically charged impurities scattering rates. The vertical transport and photoluminescence investigations are carried out in $GaAs/Al_{0.3}Ga_{0.7}As$ superlattices and asymmetric multiple quantum well modeling structures with central well of width $d_w = 25$ nm ($\epsilon_1 = 7$, $\epsilon_2 = 29$, $\epsilon_3 = 64$, $\epsilon_4 = 113$, $\epsilon_5 = 173$ meV, the lasing transition wave lengths around 60 μm [1, 2]) revealing the incoherent behavior of the resonant tunneling when it is combined with a relaxation process, resulting in the essential dependence of the tunneling time on the relaxation rate. The space charge effects are demonstrated resulting in disalignment of the resonant states and transformation of the whole resonant tunneling structure under electrical fields, which change dramatically the rate characteristics of resonant tunneling. The experimental evidence of the resonant tunneling as an effective way for selective redistribution of carriers resulting in population inversion throughout the lowest subbands in wide quantum well structure is shown.

Scattering relaxation carrier life-times

The experimentally confirmed theoretical estimates show that in structures considered the optic-phonon carrier relaxation between excited states results in $\tau^{opt} \approx 0.5$ ps while the acoustic-phonon intersubband relaxation between the first excited and the ground states results in $\tau_{12}^{ac} \approx 300$ ps at low temperatures [3, 4]. This value strongly decreases in electric field due to ionized-impurity scattering. The estimates of τ_{12} due to ionized-impurity scattering were made in analytical form taking into account the screening effect by free electrons that, as was shown, plays a noticeable role in structures with rather wide wells. The interaction between an electron and an ionized impurity scatterer centered at $z = z_i$ was described by a potential $\phi(\rho, z, z_i)$ which has been found in quasi-two-dimensional approximation from Poisson's equations (q_0 is reciprocal screening length, z is distance from the ionized impurity in-grown direction). The results of calculation with use of a standard program for computation of the probabilities of intersubband transitions for unscreened ($q_0 = 0$) and screened ionized impurities in $GaAs/Al_{0.3}Ga_{0.7}As$ quantum wells ($d_w = 25$ nm, $d_b = 4$ nm, $N_s = 10^{10}\,cm^{-2}$, $T = 4.2$ K) are presented to show that the relaxation time increases noticeably due to screening, decreases distinctly with increasing the well width, depending strongly on the impurity center location in the well. The τ_{21}^{imp} values in uniformly doped wells averaged over the impurity positions are about 40 ps ($N_d = 10^{16}\,cm^{-3}$, $N_s = 10^{10}\,cm^{-2}$) which can be increased using the selective doping (in the well center where the square of the wave function in the first excited state goes to zero). It can be shown that the electron-electron scattering does not play a decisive role in the situation [5].

Resonant coherent and incoherent tunneling rates and selectivity in structures with broadened energy levels

In view of the estimates the problem of resonant tunneling becomes to be the very important and calls for particular attention. The experiments show that the resonant tunneling times usually estimated from the energy-level splitting $\tau_{tun}^{coherent} \cong \hbar/\delta\epsilon_{split}$ are as a rule essentially longer. The main reason is the necessity of taking into account the level widths which can be caused, in particular, by carrier relaxation in neighboring well, that makes the tunneling process incoherent. According with the nonstationary quantum perturbation theory the resonant tunneling combined with the fast relaxation process in neighboring well has [6, 7] as a result:

$$\tau_{tun}^{incoherent} \cong \tau^{opt} + \frac{\hbar}{\delta\epsilon_{split}} \left(\frac{\gamma}{\delta\epsilon_{split}}\right) \frac{\Delta\epsilon^2 + \gamma^2}{\gamma^2} \tag{1}$$

where $\Delta\epsilon$ is mismatch of the resonant levels, g — half-width of the final tunneling level. The value τ_{tun} under exact resonance is proportional to $\delta\epsilon_{split}^2$ and increase with increasing of the level width as $\gamma/\delta\epsilon_{split}$. The experimental vertical transport and photoluminescence investigations are presented [2] to be consistent with (1) resulting in the values τ_{tun} for tunneling transitions $\epsilon_1 \rightarrow \epsilon_2$ in the modeling structure of about 30 ps ($d_B = 6$ nm), 10 ps ($d_B = 4$ nm), 3 ps ($d_B = 2$ nm) based on the calculated $\delta\epsilon_{split} = 0.5$, 1 and 3 meV.

It is shown with use of the far infrared emission [9], photoluminescence and vertical transport investigations [1, 2] that the lowest subbands are manifested separately in superlattices with $d \leq 35$ nm (the lowest level widths are of order 1–2 meV) revealing the proof that the resonant tunneling can be used for selective depopulation of the lowest levels leading to a population inversion in the structures.

Space charge mismatching of resonant levels in electric fields

The vertical transport measurements are presented to reveal a large variety of the effects that extremely change the resonant tunneling behavior and the electrical properties of the

WQWS under electrical fields. These peculiarities have been investigated in detail being caused by the carrier redistribution in the structures leading to a mismatch of the resonant levels and breaking the system down to the areas with different electric field strength (electric-field domains) [1, 2, 9–10]. These effects can be overcome but merit detailed consideration.

Optical intersubband absorption and amplification in wide-quantum-well-structures

The intersubband optical absorption coefficient for transitions between two first excited and the ground subbands in GaAs/$Al_{0.3}Ga_{0.7}$As structure evaluated on the base of analytically [2] obtained expression

$$\alpha_{12}^{\text{inter}} = \frac{512}{9}\frac{e^2(\epsilon_F - \epsilon_1)\Gamma}{mc\eta\omega d_w^3[(\epsilon_2 - \epsilon_1 - \hbar\omega)^2 + \Gamma^2]} \qquad (2)$$

the is of order $\alpha_{12}^{\text{inter}} = 4 \times 10^3\,\text{cm}^{-1}$ at carrier concentration $10^{16}\,\text{cm}^{-3}$ ($d_w = 25$ nm, $d_b = 4$ nm, $\Gamma = 5$ meV, $\epsilon_2 - \epsilon_1 = 22$ meV, 4.2 K). Here ϵ_F—Fermi energy, Γ—level width, η—refractive index, e and m—electron charge and effective mass. Taking into account the estimates for free carrier absorption (less than $10\,\text{cm}^{-1}$) [2] and for phonon absorption (less than $10\,\text{cm}^{-1}$) [2] one can conclude that the very small population inversion in the lowest subbands may result in a drastic increasing of the intensity of emission due to transitions between these states. This point plays an essential role appearing to be stimulating for laser investigations not only in WQWS but also in multiple WQWS as well.

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